Chapter 3
Riprap Protection

Section I
Introduction

3-1. General

* The guidance presented herein applies to riprap design for open channels not immediately downstream of stilling basins or other highly turbulent areas (for stilling basin riprap, use HDC 712-1, Plates 29 and 30). The ability of riprap slope protection to resist the erosive forces of channel flow depends on the interrelation of the following factors: stone shape, size, weight, and durability; riprap gradation and layer thickness; and channel alignment, cross-section, gradient, and velocity distribution. The bed material and local scour characteristics determine the design of toe protection which is essential for riprap revetment stability. The bank material and groundwater conditions affect the need for filters between the riprap and underlying material. Construction quality control of both stone production and riprap placement is essential for successful bank protection. Riprap protection for flood control channels and appurtenant structures should be designed so that any flood that could reasonably be expected to occur during the service life of the channel or structure would not cause damage exceeding nominal maintenance or replacement (see ER 1110-2-1150). While the procedures presented herein yield definite stone sizes, results should be used for guidance purposes and revised as deemed necessary to provide a practical protection design for the specific project conditions.

3-2. Riprap Characteristics

The following provides guidance on stone shape, size/weight relationship, unit weight, gradation, and layer thickness. Reference EM 1110-2-2302 for additional guidance on riprap material characteristics and construction.

a. Stone shape. Riprap should be blocky in shape rather than elongated, as more nearly cubical stones "nest" together best and are more resistant to movement. The stone should have sharp, angular, clean edges at the intersections of relatively flat faces. Stream rounded stone is less resistant to movement, although the drag force on a rounded stone is less than on angular, cubical stones. As rounded stone interlock is less than that of equal-sized angular stones, the rounded stone mass is more likely to be eroded by channel flow. If used, the rounded stone should be placed on flatter side slopes than angular stone and should be about 25 percent larger in diameter. The following shape limitations should be specified for riprap obtained from quarry operations:

(1) The stone shall be predominantly angular in shape.

(2) Not more than 30 percent of the stones distributed throughout the gradation should have a ratio of a/c greater than 2.5. *

(3) Not more than 15 percent of the stones distributed throughout the gradation should have a ratio of a/c greater than 3.0.

(4) No stone should have a ratio of a/c greater than 3.5.

To determine stone dimensions a and c, consider that the stone has a long axis, an intermediate axis, and a short axis, each being perpendicular to the other. Dimension a is the maximum length of the stone, which defines the long axis of the stone. The intermediate axis is defined by the maximum width of the stone. The remaining axis is the short axis. Dimension c is the maximum dimension parallel to the short axis. These limitations apply only to the stone within the required riprap gradation and not to quarry spalls and waste that may be allowed.

b. Relation between stone size and weight. The ability of riprap revetment to resist erosion is related to the size and weight of stones. Design guidance is often expressed in terms of the stone size $D_{\%}$, where % denotes the percentage of the total weight of the graded material (total weight including quarry wastes and spalls) that contains stones of less weight. The relation between size and weight of stone is described herein using a spherical shape by the equation

$$D_{\%} = \left(\frac{6W_{\%}}{\pi \gamma_s} \right)^{1/3} \qquad (3\text{-}1)$$

where

$D_{\%}$ = equivalent-volume spherical stone diameter, ft

$W_{\%}$ = weight of individual stone having diameter of $D_{\%}$

γ_s = saturated surface dry specific or unit weight of stone, pcf

Plate 31 presents relations between spherical diameter and weight for several values of specific or unit weight. Design procedures for determining the stone size required to resist the erosive forces of channel flow are presented in paragraph 3-5 below.

c. Unit weight. Unit weight of stone γ_s generally varies from 150 to 175 pcf. Riprap sizing relations are relatively sensitive to unit weight of stone, and γ_s should be determined as accurately as possible. In many cases, the unit weight of stone is not known because the quarry is selected from a list of approved riprap sources after the construction contract is awarded. Riprap coming from the various quarries will not be of the same unit weight. Under these circumstances, a unit weight of stone close to the minimum of the available riprap sources can be used in design. Contract options covering specific weight ranges of 5 or 10 pcf should be offered when sufficient savings warrant.

d. Gradation.

(1) The gradation of stones in riprap revetment affects the riprap's resistance to erosion. Stone should be reasonably well graded throughout the in-place layer thickness. Specifications should provide for two limiting gradation curves, and any stone gradation as determined from quarry process, stockpile, <u>and</u> in-place field test samples that lies within these limits should be acceptable. Riprap sizes and weights are frequently used such as D_{30}(min), D_{100}(max), W_{50}(min), etc. The D or W refers to size or weight, respectively. The number is the percent finer by weight as discussed in b above. The (max) or (min) refers to the upper or lower limit gradation curves, respectively. Engineer Form 4794-R is a standard form for plotting riprap gradation curves (Plate 32). The gradation limits should not be so restrictive that production costs would be excessive. The choice of limits also depends on the underlying bank soils and filter requirements if a graded stone filter is used. Filters may be required under riprap revetments. Guidance for filter requirements is given in EM 1110-2-1901. Filter design is the responsibility of the Geotechnical Branch in each District.

(2) Standardized gradations having a relatively narrow range in sizes (D_{85}/D_{15} of 1.4-2.2) are shown in Table 3-1. Other gradations can be used and often have a wider range of allowable sizes than those given in Table 3-1. One example is the Lower Mississippi Valley Division (LMVD) Standardized Gradations presented in Appendix F. The LMVD gradations are similar to the gradations listed in Table 3-1 except the LMVD W_{50}(max) and W_{15}(max) weights are larger, which can make the LMVD gradations easier to produce. Most graded ripraps have ratios of D_{85}/D_{15} less than 3. Uniform riprap ($D_{85}/D_{15} < 1.4$) has been used at sites in the US Army Engineer Division, Missouri River, for reasons of economy and quality control of sizes and placement.

(3) Rather than a relatively expensive graded riprap, a greater thickness of a quarry-run stone may be considered. Some designers consider the quarry-run stone to have another advantage: its gravel- and sand-size components serve as a filter. The gravel and sand sizes should be less by volume than the voids among the larger stone. This concept has resulted in considerable cost savings on large projects such as the Arkansas and Red River Navigation Projects. Not all quarry-run stone can be used as riprap; stone that is gap graded or has a large range in maximum to minimum size is probably unsuitable. Quarry-run stone for riprap should be limited to $D_{85}/D_{15} \leq 7$.

(4) Determining optimum gradations is also an economics problem that includes the following factors:

(a) Rock quality (durability under service conditions)

(b) Cost per ton at the quarry (including capability of quarry to produce a particular size)

(c) Number of tons required

(d) Miles transported

(e) Cost of transportation per ton-mile

(f) Cost per ton for placement

(g) Need for and cost of filter

(h) Quality control during construction (it is easier to ensure even coverage with a narrow gradation than with a wide gradation)

(i) Number of different gradations required. Sometimes cost savings can be realized by using fewer gradations.

See EM 1110-2-2302 for further discussion of these factors.

Table 3-1
Gradations for Riprap Placement in the Dry, Low-Turbulence Zones

Limits of Stone Weight, lb[1], for Percent Lighter by Weight

D_{100}(max)	100		50		15		D_{30}(min)	D_{90}(min)
in.	Max	Min	Max[2]	Min	Max[2]	Min	ft	ft
Specific Weight = 155 pcf								
* 9	34	14	10	7	5	2	0.37	0.53 *
12	81	32	24	16	12	5	0.48	0.70
15	159	63	47	32	23	10	0.61	0.88
18	274	110	81	55	41	17	0.73	1.06
21	435	174	129	87	64	27	0.85	1.23
24	649	260	192	130	96	41	0.97	1.40
27	924	370	274	185	137	58	1.10	1.59
30	1,268	507	376	254	188	79	1.22	1.77
33	1,688	675	500	338	250	105	1.34	1.94
36	2,191	877	649	438	325	137	1.46	2.11
42	3,480	1,392	1,031	696	516	217	1.70	2.47
48	5,194	2,078	1,539	1,039	769	325	1.95	2.82
54	7,396	2,958	2,191	1,479	1,096	462	2.19	3.17
Specific Weight = 165 pcf								
* 9	36	15	11	7	5	2	0.37	0.53 *
12	86	35	26	17	13	5	0.48	0.70
15	169	67	50	34	25	11	0.61	0.88
18	292	117	86	58	43	18	0.73	1.06
21	463	185	137	93	69	29	0.85	1.23
24	691	276	205	138	102	43	0.97	1.40
27	984	394	292	197	146	62	1.10	1.59
30	1,350	540	400	270	200	84	1.22	1.77
33	1,797	719	532	359	266	112	1.34	1.96
36	2,331	933	691	467	346	146	1.46	2.11
42	3,704	1,482	1,098	741	549	232	1.70	2.47
48	5,529	2,212	1,638	1,106	819	346	1.95	2.82
54	7,873	3,149	2,335	1,575	1,168	492	2.19	3.17
Specific Weight = 175 pcf								
* 9	39	15	11	8	6	2	0.37	0.53 *
12	92	37	27	18	14	5	0.48	0.70
15	179	72	53	36	27	11	0.61	0.88
18	309	124	92	62	46	19	0.73	1.06
21	491	196	146	98	73	31	0.85	1.23
24	733	293	217	147	109	46	0.97	1.40
27	1,044	417	309	209	155	65	1.10	1.59
30	1,432	573	424	286	212	89	1.22	1.77
33	1,906	762	565	381	282	119	1.34	1.94
36	2,474	990	733	495	367	155	1.46	2.11
42	3,929	1,571	1,164	786	582	246	1.70	2.47
48	5,864	2,346	1,738	1,173	869	367	1.95	2.82
54	8,350	3,340	2,474	1,670	1,237	522	2.19	3.17

Notes:
1. Stone weight limit data from ETL 1110-2-120 (HQUSACE, 1971 (14 May), “Additional Guidance for Riprap Channel Protection, Ch 1,” US Government Printing Office, Washington, DC). Relationship between diameter and weight is based on the shape of a sphere.
2. The maximum limits at the W_{50} and W_{15} sizes can be increased as in the Lower Mississippi Valley Division Standardized Gradations shown in Appendix F.

e. Layer thickness. All stones should be contained within the riprap layer thickness to provide maximum resistance against erosive forces. Oversize stones, even in isolated spots, may result in riprap failure by precluding mutual support and interlock between individual stones, causing large voids that expose filter and bedding materials, and creating excessive local turbulence that removes smaller size stone. Small amounts of oversize stone should be removed individually and replaced with proper size stones. The following criteria apply to the riprap layer thickness:

(1) It should not be less than the spherical diameter of the upper limit W_{100} stone or less than 1.5 times the spherical diameter of the upper limit W_{50} stone, whichever results in the greater thickness.

(2) The thickness determined by (1) above should be increased by 50 percent when the riprap is placed underwater to provide for uncertainties associated with this type of placement. At one location in the US Army Engineer Division, Missouri River, divers and sonic sounders were used to reduce the underwater thickness to 1.25 times the dry placement thickness.

Section II
Channel Characteristics

3-3. Side Slope Inclination

The stability of riprap slope protection is affected by the steepness of channel side slopes. Side slopes should ordinarily not be steeper than 1V on 1.5H, except in special cases where it may be economical to use larger hand-placed stone keyed well into the bank. Embankment stability analysis should properly address soils characteristics, groundwater and river conditions, and probable failure mechanisms. The size of stone required to resist the erosive forces of channel flow increases when the side slope angle approaches the angle of repose of a riprap slope protection. Rapid water-level recession and piping-initiated failures are other factors capable of affecting channel side slope inclination and needing consideration in design.

3-4. Channel Roughness, Shape, Alignment, and Gradient

As boundary shear forces and velocities depend on channel roughness, shape, alignment, and invert gradient, these factors must be considered in determining the size of stone required for riprap revetment. Comparative cost estimates should be made for several alternative channel plans to determine the most economical and practical combination of channel factors and stone size. Resistance coefficients (Manning's n) for riprap placed in the dry should be estimated using the following form of Strickler's equation:

$$n = K \left[D_{90}(\text{min})\right]^{1/6} \tag{3-2}$$

where

K = 0.036, average of all flume data

= 0.034 for velocity and stone size calculation

= 0.038 for capacity and freeboard calculation

$D_{90}(\text{min})$ = size of which 90 percent of sample is finer, from minimum or lower limit curve of gradation specification, ft

The K values represent the upper and lower bounds of laboratory data determined for bottom riprap. Resistance data from a laboratory channel which had an irregular surface similar to riprap placed underwater show a Manning's n about 15 percent greater than for riprap
* placed in the dry. Equation 3-2 provides resistance losses due to the surface roughness of the riprap and does not include form losses such as those caused by bends. Equation 3-2 should be limited to slopes less than 2 percent. *

Section III
Design Guidance for Stone Size

3-5. General

Riprap protection for open channels is subjected to hydrodynamic drag and lift forces that tend to erode the revetment and reduce its stability. Undermining by scour beyond the limits of protection is also a common cause of failure. The drag and lift forces are created by flow velocities adjacent to the stone. Forces resisting motion are the submerged weight of the stone and any downward and lateral force components caused by contact with other stones in the revetment. Stone availability and experience play a large part in determining size of riprap. This is particularly true on small projects where hydraulic parameters are ill-defined and the total amount of riprap required is small.

3-6. Design Conditions

Stone size computations should be conducted for flow conditions that produce the maximum velocities at the riprapped boundary. In many cases, velocities continue to increase beyond bank-full discharge; but sometimes backwater effects or loss of flow into the overbanks results in velocities that are less than those at bank-full. Riprap at channel bends is designed conservatively for the point having the maximum force or velocity. For braided channels, bank-full discharges may not be the most severe condition. At lesser flows, flow is often divided into multiple channels. Flow in these channels often impinges abruptly on banks or levees at sharp angles.

3-7. Stone Size

This method for determining stone size uses depth-averaged local velocity. The method is based on the idea that a designer will be able to estimate local velocity better than local boundary shear. Local velocity and local flow depth are used in this procedure to quantify the imposed forces. Riprap size and unit weight quantify the resisting force of the riprap. This method is based on a large body of laboratory data and has been compared to available prototype data (Maynord 1988). It defines the stability of a wide range of gradations if placed to a thickness of $1D_{100}$(max). Guidance is also provided for thickness greater than $1D_{100}$(max). This method is applicable to side slopes of 1V on 1.5H or flatter.

a. Velocity estimation. The characteristic velocity for side slopes V_{SS} is the depth-averaged local velocity over the slope at a point 20 percent of the slope length from the toe of slope. Plate 33 presents the ratio V_{SS}/V_{AVG} , where V_{AVG} is the average channel velocity at the upstream end of the bend, as a function of the channel geometry, which is described by R/W , where R is the center-line radius of bend and W is the water-surface width. V_{AVG} , R , and W should be based on flow in the main channel only and should not include overbank areas. The trapezoidal curve for V_{SS}/V_{AVG} shown in Plate 33 is based on the STREMR numerical model described in Bernard (1993). The primary factors affecting velocity distribution in riprap-lined, trapezoidal channel bendways are R/W , bend angle, and aspect ratio (bottom width/depth). Data in Maynord (1992) show a trapezoidal channel having the same bottom width but side slopes ranging from 1V:1.5H to 1V:3H to have the same maximum V_{SS}/V_{AVG} at the downstream end of the bend. Plate 33 should be used for side slopes from 1V:3H to 1V:1.5H. For straight channels sufficiently far (>5W) from upstream bends, large values of R/W should be used, resulting in constant values of V_{SS}/V_{AVG} . Very few channels are straight enough to justify using $V_{SS}/V_{AVG} < 1$. A minimum ratio of $V_{SS}/V_{AVG} = 1$ is recommended for side slopes in straight channels. Rock stability should be checked for both side slopes and the channel bottom. In bendways, the outer bank side slope will generally require the largest rock size. In straight reaches, the channel bottom will often require the largest stone size. Velocities in the center of a straight channel having equal bottom and side slope roughness range from 10 to 20 percent greater than V_{AVG} . Plate 34 describes V_{SS} and Plate 35 shows the location in a trapezoidal channel bend of the maximum V_{SS} . Velocity downstream of bends decays at approximately the following rate: No decay in first channel width downstream of bend exit; decay of $V_{SS}/V_{AVG} = 0.1$ per channel width until $V_{SS}/V_{AVG} = 1.0$. Plate 36 shows the variation in velocity over the side slope in a channel. The straight channel curve in Plate 36 was found applicable to both 1V:2H and 1V:3H side slopes. The bend curve for R/W = 2.6 was taken from a channel having strong secondary currents and represents a severe concentration of high velocity upon the channel side slope. These two curves represent the extremes in velocity distribution to be expected along the outer bank of a channel bend having a riprap side slope from toe of bank to top of bank. Knowing V_{SS} from Plate 33, the side slope velocity distribution can be determined at the location of V_{SS}. An alternate means of velocity estimation based on field observation is discussed in Appendix G. The alpha method (Appendix C), or velocities resulting from subsections of a water-surface profile computation, should be used only in straight reaches. When the alpha method is used, velocity from the subsection adjacent to the bank subsection should be used as V_{SS} in design of bank riprap.

b. Stone size relations. The basic equation for the representative stone size in straight or curved channels is

$$D_{30} = S_f C_s C_V C_T d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5} \qquad (3\text{-}3)$$

where

D_{30} = riprap size of which 30 percent is finer by weight, length

S_f = safety factor (see *c* below)

* C_s = stability coefficient for incipient failure, D_{85}/D_{15} = 1.7 to 5.2

= 0.30 for angular rock

* = 0.375 for rounded rock

C_V = vertical velocity distribution coefficient

= 1.0 for straight channels, inside of bends

= 1.283 - 0.2 log (R/W), outside of bends (1 for (R/W) > 26)

= 1.25, downstream of concrete channels

= 1.25, ends of dikes

C_T = thickness coefficient (see d(1) below)

* = 1.0 for thickness = $1D_{100}$(max) or 1.5 D_{50}(max), whichever is greater

* d = local depth of flow, length (same location as *V*)

γ_w = unit weight of water, weight/volume

* V = local depth-averaged velocity, V_{SS} for side slope riprap, length/time

K_1 = side slope correction factor (see *d*(1) below)

g = gravitational constant, length/time^2

* Some designers prefer to use the traditional D_{50} in riprap design. The approximate relationship between D_{50} and D_{30} is $D_{50} = D_{30}\ (D_{85}/D_{15})^{1/3}$. Equation 3-3 can be used with either SI (metric) or non-SI units and should be limited to slopes less than 2 percent.

c. Safety factor. Equation 3-3 gives a rock size that should be increased to resist hydrodynamic and a variety of nonhydrodynamic-imposed forces and/or uncontrollable physical conditions. The size increase can best be accomplished by including the safety factor, which will be a * value greater than unity. The minimum safety factor is * S_f = 1.1 . The minimum safety factor may have to be increased in consideration for the following conditions:

(1) Imposed impact forces resulting from logs, uprooted trees, loose vessels, ice, and other types of large floating debris. Impact will produce more damage to alighter weight riprap section than to a heavier section. For moderate debris impact, it is unlikely that an added * safety factor should be used when the blanket thickness exceeds 15 in.

(2) The basic stone sizing parameters of velocity, * unit weight of rock, and depth need to be determined as accurately as possible. A safety factor should be included to compensate for small inaccuracies in these parameters. If conservative estimates of these parameters are used in the analysis, the added safety factor should not be used. The safety factor should be based on the anticipated error in the values used. The following discussion shows the importance of obtaining nearly correct values rather than relying on a safety factor to correct inaccurate or assumed stone sizing parameters. The average velocity over the toe of the riprap is an estimate at best and is the parameter to which the rock size is the most sensitive. A check of the sensitivity will show that a 10 percent change in velocity will result in a nearly 100 percent change in the weight limits of the riprap gradation (based on a sphere) and about a 30 percent change in the riprap * thickness. The riprap size is also quite sensitive to the unit weight of the rock to be used: a 10 percent change in the * unit weight will result in a 70 percent change in the weight limits of the riprap gradation (based on a sphere) and about a 20 percent change in the riprap thickness. The natural variability of unit weight of stone from a stone source adds to the uncertainty (EM 1110-2-2302). * The rock size is not nearly as sensitive to the depth parameter.

(3) Vandalism and/or theft of the stones is a serious problem in urban areas where small riprap has been placed. A W_{50}(min) of 80 lb should help prevent theft and vandalism. Sometimes grouted stone is used around vandalism-prone areas.

(4) The completed revetment will contain some * pockets of undersized rocks, no matter how much effort is devoted to obtaining a well-mixed gradation throughout the revetment. This placement problem can be assumed to occur on any riprap job to some degree but probably more frequently on jobs that require stockpiling or additional handling. A larger safety factor should be considered with stockpiling or additional hauling and where placement will be difficult if quality control cannot be expected to address these problems.

(5) The safety factor should be increased where severe freeze-thaw is anticipated.

The safety factor based on each of these considerations should be considered separately and then the largest of these values should be used in Equation 3-3.

d. Applications.

(1) The outer bank of straight channels downstream of bends should be designed using velocities computed for the bend. In projects where the cost of riprap is high, a channel model to indicate locations of high velocity might be justified. Equation 3-3 has been developed into Plate 37, which is applicable to thicknesses equal to $1D_{100}$(max), γ_s of 165 pcf, and the S_f of 1.1. Plate 38 is used to correct for values of other than γ_s of 165 pcf (when D_{30} is determined from Plate 37). The K_1 side slope factor is normally defined by the relationship of Carter, Carlson, and Lane (1953)

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} \tag{3-4}$$

where

θ = angle of side slope with horizontal

ϕ = angle of repose of riprap material (normally 40 deg)

Results given in Maynord (1988) show Equation 3-4 to be conservative and that the repose angle is not a constant 40 deg but varies with several factors. The recommended relationship for K_1 as a function of θ is given in Plate 39 along with Equation 3-4 using ϕ = 40 deg. Using the recommended curve for side slope effects, the least volume of rock per unit length of bank line occurs on a 1V:1.5H to 1V:2H side slope. Also shown on Plate 39 is the correction for side slope when D_{30} is determined from Plate 37. Correction for the vertical velocity distribution in bends is shown in Plate 40. Testing has been conducted to determine the effects of blanket thickness greater than $1D_{100}$(max) on the stability of riprap. Results are shown in Plate 40. The thickness coefficient C_T accounts for the increase in stability that occurs when riprap is placed thicker than the minimum thickness of $1D_{100}$(max) or 1.5 D_{50}(max), whichever is greater.

(2) The basic procedure to determine riprap size using the graphical solution of this method is as follows:

(a) Determine average channel velocity (HEC-2 or other uniform flow computational methods, or measurement).

(b) Find V_{SS} using Plate 33.

(c) Find D_{30} using Plate 37.

(d) Correct for other unit weights, side slopes, vertical velocity distribution, or thicknesses using Plates 38 through 40.

(e) Find gradation having D_{30}(min) $\geq$ computed D_{30}. Alternately Equation 3-3 is used with Plates 39 and 40 to replace steps (c) and (d).

(3) This procedure can be used in both natural channels with bank protection only and prismatic channels having riprap on bed and banks. Most bank protection sections can be designed by direct solution. In these cases, the extent of the bank compared to the total perimeter of the channel means that the average channel velocity is not significantly affected by the riprap. The first example in Appendix H demonstrates this type of bank protection.

(4) In some cases, a large part of the channel perimeter is covered with riprap; the average channel velocity, depth, and riprap size are dependent upon one another; and the solution becomes iterative. A trial riprap gradation is first assumed and resistance coefficients are computed using Equation 3-2. Then the five steps described in (2) above are conducted. If the gradation found in paragraph (e) above is equal to the assumed trial gradation, the solution is complete. If not, a new trial gradation is assumed and the procedure is repeated. The second example in Appendix H demonstrates this type of channel riprap.

(5) In braided streams and some meandering streams, flow is often directed into the bank line at sharp angles (angled flow impingement). For braided streams having impinged flow, the above stone sizing procedures require modification in two areas: the method of velocity estimation and the velocity distribution coefficient C_V. All other factors and coefficients presented are applicable.

(a) The major challenge in riprap design for braided streams is estimating the imposed force at the impingement point. Although unproven, the most severe bank

* attack in braided streams is thought to occur when the water surface is at or slightly above the tops of the mid-channel bars. At this stage, flow is confined to the multiple channels that often flow into or "impinge" against bank lines or levees. At lesser flows, the depths and velocities in the multiple channels are decreased. At higher flows, the channel area increases drastically and streamlines are in a more downstream direction rather than into bank lines or levees.

(b) The discharge that produces a stage near the tops of the midchannel bars is Q_{tmcb} . Q_{tmcb} is probably highly correlated with the channel-forming discharge concept. In the case of the Snake River near Jackson, Wyoming, Q_{tmcb} is 15,000-18,000 cfs, which has an average recurrence interval of about 2-5 years. Using cross-section data to determine the channel area below the tops of the midchannel bars and Q_{tmcb} allows determination of the average channel velocity at the top of the midchannel bars, V_{tmcb} .

(c) Field measurements at impingement sites were taken in 1991 on the Snake River near Jackson, Wyoming, and reported in Maynord (1993). The maximum observed ratio $V_{SS}/V_{tmcb} = 1.6$, which is almost identical to the ratio shown in Plate 33 for sharp bendways having $R/W = 2$ in natural channels, and this ratio is recommended for determining V_{SS} for impinged flow. The second area of the design procedure requiring modification for impinged flow is the velocity distribution coefficient C_V , which varies with R/W in bendways as shown in Plate 40. Impinged flow areas are poorly aligned bends having low R/W , and $C_V = 1.25$ is recommended for design.

(6) Transitions in size or shape may also require riprap protection. The procedures in this paragraph are applicable to gradual transitions where flow remains tranquil. In areas where flow changes from tranquil to rapid and then back to tranquil, riprap sizing methods applicable to hydraulic structures (HDC 712-1) should be used. In converging transitions, the procedures based on Equation 3-3 can be used unaltered. In expanding transitions, flow can concentrate on one side of the expansion and design velocities should be increased. For installations immediately downstream of concrete channels, a vertical velocity distribution coefficient of 1.25 should be used due to the difference in velocity profile over the two surfaces.

* *e. Steep slope riprap design.*

In cases where unit discharge is low, riprap can be used on steep slopes ranging from 2 to 20 percent. A typical application is a rock-lined chute. The stone size equation is

$$D_{30} = \frac{1.95\ S^{0.555}\ q^{2/3}}{g^{1/3}} \qquad (3\text{-}5)$$

where

S = slope of bed

q = unit discharge

Equation 3-5 is applicable to thickness = 1.5 D_{100}, angular rock, unit weight of 167 pcf, D_{85}/D_{15} from 1.7 to 2.7, slopes from 2 to 20 percent, and uniform flow on a down-slope with no tailwater. The following steps should be used in application of Equation 3-5:

(1) Estimate $q = Q/b$ where b = bottom width of chute.

(2) Multiply q by flow concentration factor of 1.25. Use greater factor if approach flow is skewed.

(3) Compute D_{30} using Equation 3-5.

(4) Use uniform gradation having $D_{85}/D_{15} \le 2$ such as Table 3-1.

* (5) Restrict application to straight channels with side slope of 1V:2.5H or flatter.

(6) Use filter fabric beneath rock.

The guidance for steep slope riprap generally results in large riprap sizes. Grouted riprap is often used instead of loose riprap in steep slope applications. *

3-8. Revetment Top and End Protection

Revetment top and end protection requirements, as with all channel protective measures, are to assure the project benefits, to perform satisfactorily throughout the project economic life, and not to exceed reasonable maintenance costs. Reference is made to ER 1110-2-1405, with emphasis on paragraph 6*c*.

a. Revetment top. When the full height of a levee is to be protected, the revetment will cover the freeboard, i.e., extend to the top of the levee. This provides protection against waves, floating debris, and water-surface irregularities. Similar provisions apply to incised channel banks. A horizontal collar, at the top of the bank, is provided to protect against escaping and returning flows as necessary. The end protection methods illustrated in Plate 41 can be adapted for horizontal collars. Plate 36 provides general guidance for velocity variation over channel side slopes that can assist in evaluating the economics of reducing or omitting revetment for upper bank areas. Revetment size changes should not be made unless a sufficient quantity is involved to be cost effective. Many successful revetments have been constructed where the top of the revetment was terminated below the design flow line. See USACE (1981) for examples.

b. Revetment end protection. The upstream and downstream ends of riprap revetment should be protected against erosion by increasing the revetment thickness T or extending the revetment to areas of noneroding velocities and relatively stable banks. A smooth transition should be provided from where the end protection begins to the design riprap section. The keyed-in section should satisfy filter requirements. The following guidance applies to the alternative methods of end protection illustrated in Plate 41.

(1) Method A. For riprap revetments 12 in. thick or less, the normal riprap layer should be extended to areas where velocities will not erode the natural channel banks.

(2) Method B. For riprap revetments exceeding 12 in. in thickness, one or more reductions in riprap thickness and stone size may be required (Plate 41) until velocities decrease to a noneroding natural channel velocity.

(3) Method C. For all riprap revetments that do not terminate in noneroding natural channel velocities, the ends of the revetment should be enlarged, as shown in Plate 41. The decision to terminate the revetment in erosive velocities should be made with caution since severe erosion can cause the revetment to fail by progressive flanking.

c. Length. Riprap revetment is frequently carried too far upstream and not far enough downstream of a channel bend. In a trapezoidal channel, the maximum velocities along the outer bank are often located in the straight reach immediately downstream of the bend for relatively large distances downstream. In a natural channel, the limit of protection on the downstream end should depend on where the flow crosses to the opposite bank, and should consider future bar building on the opposite bank, resulting in channel constriction and increased velocities. Guidance is generally lacking in this area, but review of aerial photographs of the subject location can provide some insight on where the crossover flow occurs. Model tests in a sand bed and bank flume (USACE 1981) were conducted to determine the limits of protection required to prevent scour that would lead to destruction of the revetment. These tests were conducted in a 110-deg bend having a constant discharge. The downstream end of the revetment had to be 1.5 channel widths downstream of the end of the bend. Geomorphic studies to determine revetment ends should be considered.

Section IV
Revetment Toe Scour Estimation and Protection

3-9. General

Toe scour is probably the most frequent cause of failure of riprap revetments. This is true not only for riprap, but also for a wide variety of protection techniques. Toe scour is the result of several factors, including these three:

a. Meandering channels, change in cross section that occurs after a bank is protected. In meandering channels the thalweg often moves toward the outer bank after the bank is protected. The amount of change in cross section that occurs after protection is added is related to the erodibility of the natural channel bed and original bank material. Channels with highly erodible bed and banks can experience significant scour along the toe of the new revetment.

b. Meandering channels, scour at high flows. Bed profile measurements have shown that the bed observed at low flows is not the same bed that exists at high flows. At high flows the bed scours in channel bends and builds up in the crossings between bends. On the recession side of the flood, the process is reversed. Sediment is eroded from the crossings and deposited in the bends, thus obscuring the maximum scour that had occurred.

c. Braided channels. Scour in braided channels can reach a maximum at intermediate discharges where flow in the channel braids attacks banks at sharp angles.

Note that local scour is the mechanism being addressed herein. When general bed degradation or headcutting is expected, it must be added to the local scour. When scour mechanisms are not considered in the design of protection works, undermining and failure may result. Plate 42 may be used for depth of scour estimates. The design curve in Plate 42 represents an upper limit for scour in channels having irregular alignments. For bendways having a relatively smooth alignment, a 10 percent reduction from the design curve is recommended. Neill (1973) provides additional information on scour depth estimation.

3-10. Revetment Toe Protection Methods

Toe protection may be provided by two methods:

a. Extend to maximum scour depth. Place the lower extremity below the expected scour depth or found it on nonerodible material. These are the preferred methods, but they can be difficult and expensive when underwater excavation is required.

b. Place launchable stone. Place sufficient launchable stone to stabilize erosion. Launchable stone is defined as stone that is placed along expected erosion areas at an elevation above the zone of attack. As the attack and resulting erosion occur below the stone, the stone is undermined and rolls/slides down the slope, stopping the erosion. This method has been widely used on <u>sand bed streams</u>. Successful applications include:

(1) Windrow revetments: riprap placed at top of bank.

(2) Trench-fill revetments: riprap placed at low water level.

(3) Weighted riprap toes: riprap placed at intersection of channel bottom and side slope.

Trench-fill revetments on the Mississippi River have successfully launched to protect for a vertical scour depth of up to 50 ft. On gravel bed streams, the use of launchable stone is not as widely accepted as in sand bed streams. Problems with using launchable stone in some gravel bed rivers may be the result of underestimating stone size, scour depth, or launchable stone volume because the concept of launchable stone has been successful on several gravel bed rivers.

3-11. Revetment Toe Protection Design

The following guidance applies to several alternative methods of toe protection illustrated in Plate 43.

a. Method A. When toe excavation can be made in the dry, the riprap layer may be extended below the existing groundline a distance exceeding the anticipated depth of scour. If excavation quantities are prohibitive, the concept of Method D can be adapted to reduce excavation.

b. Method B. When the bottom of the channel is nonerodible material, the normal riprap should be keyed in at streambed level.

c. Method C. When the riprap is to be placed underwater and little toe scour is expected (such as in straight reaches that are not downstream of bends, unless stream is braided), the toe may be placed on the existing bottom with height a and width c equal to 1.5T and 5T , respectively. This compensates for uncertainties of underwater placement.

d. Method D. An extremely useful technique where water levels prohibit excavation for a toe section is to place a launchable section at the toe of the bank. Even if excavation is practicable, this method may be preferred for cost savings if the cost of extra stone required to produce a launched thickness equal to or greater than T plus the increase shown in Table 3-2 is exceeded by the cost of excavation required to carry the design thickness T down the slope. This concept simply uses toe scour as a substitute for mechanical excavation. This method also has the advantage of providing a “built-in” scour gage, allowing easy monitoring of high-flow scour and the need for additional stone reinforcement by visual inspection of the remaining toe stone after the high flow subsides or by surveyed cross sections if the toe stone is underwater. It is readily adaptable to emergency protection, where high flow and the requirement for quick action make excavation impractical. Shape of the stone section before launching is not critical, but thickness of the section is important because thickness controls the rate at which rock is released in the launching process. For gradual scour in regular bendways, the height of the stone section before launching should be from 2.5 to 4.0 times the bank protection thickness (T). For rapid scour in impinged flow environments or in gravel bed streams, the stone section height before launching should be 2.5 to 3.0 T. In

*

Table 3-2
Increase in Stone Volume for Riprap Launching Sections

	Volume Increase, Percent	
Vertical Launch Distance, ft[1]	Dry Placement	Underwater Placement
≤ 15	25	50
> 15	50	75

Note:
[1] From bottom of launch section to maximum scour.

any case, the thinner and wider rock sections represented by the lower values of thickness have an apparent advantage in that the rock in the stream end of the before-launch section has a lesser distance to travel in the launching process. Providing an adequate volume of stone is critical. Stone is lost downstream in the launching process; and the larger the scour depth, the greater the percentage of stone lost in the launching process. To compute the required launchable stone volume for Method D, the following assumptions should be used:

(1) Launch slope = 1V on 2H. This is the slope resulting from rock launched on noncohesive material in both model and prototype surveys. Launch slope is less predictable if cohesive material is present, since cohesive material may fail in large blocks.

(2) Scour depth = existing elevation - maximum scour elevation.

* (3) Thickness after launching = thickness of the bank revetment T .

* To account for the stone lost during launching and for placement underwater, the increases in stone volume listed in Table 3-2 are recommended. Using these assumptions, the required stone volume for underwater placement for vertical launch distance less than 15 ft = 1.5T times launch slope length

= 1.5T times scour depth times $\sqrt{5}$

= 3.35T (scour depth)

Add a safety factor if data to compute scour depth are unreliable, if cohesive bank material is present, or if monitoring and maintenance after construction cannot be guaranteed. Guidance for a safety factor is lacking, so to some extent it must be determined by considering conse-
* quences of failure. Widely graded ripraps are recommended because of reduced rock voids that tend to prevent leaching of lower bank material through the launched riprap. Launchable stone should have $D_{85}/D_{15} \geq 2$. *

3-12. Delivery and Placement

Delivery and placement can affect riprap design. See EM 1110-2-2302 for detailed guidance. The common methods of riprap placement are hand placing; machine placing, such as from a skip, dragline, or some form of bucket; and dumping from trucks and spreading by bulldozer. Hand placement produces the most stable riprap revetment because the long axes of the riprap particles are oriented perpendicular to the bank. It is the most expensive method except when stone is unusually costly and/or labor unusually cheap. Steeper side slopes can be used with hand-placed riprap than with other placing methods. This reduces the required volume of rock. However, the greater cost of hand placement usually makes machine or dumped placement methods and flatter slopes more economical. Hand placement on steep slopes should be con-
* sidered when channel widths are constricted by existing bridge openings or other structures when rights-of-way are costly. In the machine placement method, sufficiently small increments of stone should be released as close to their final positions as practical. Rehandling or dragging operations to smooth the revetment surface tend to result in segregation and breakage of stone. Stone should not be dropped from an excessive height or dumped and spread as this may result in the same undesirable conditions. However, in some cases, it may be economical to increase the layer thickness and stone size somewhat to offset the shortcomings of this placement method. Smooth, compact riprap sections have resulted from compacting the placed stone sections with a broad-tracked bulldozer. This stone must be quite resistant to abrasion. Thickness for underwater placement should be increased by 50 percent to provide for the uncertainties associated with this type of placement. Underwater placement is usually specified in terms of weight of stone per unit area, to be distributed uniformly and controlled by a "grid" established by
* shoreline survey points.

Section V
Ice, Debris, and Vegetation

3-13. Ice and Debris

Ice and debris create greater stresses on riprap revetment by impact and flow concentration effects. Ice attachment to the riprap also causes a decrease in stability. The Cold Regions Research Engineering Laboratory, Hanover, NH, should be contacted for detailed guidance relative to ice effects on riprap. One rule of thumb is that thickness should be increased by 6-12 in., accompanied by appropriate increase in stone size, for riprap subject to attack by large floating debris. Riprap deterioration from debris impacts is usually more extensive on bank lines with steep slopes. Therefore, riprapped slopes on streams with heavy debris loads should be no steeper than 1V on 2.5H.

3-14. Vegetation

The guidance in this chapter is based on maintaining the riprap free of vegetation. When sediment deposits form lowflow berms on riprap installations, vegetation may be allowed on these berms under the following conditions: roots do not penetrate the riprap; failure of the riprap would not jeopardize project purposes prior to repairs; and the presence of the berm and vegetation does not significantly reduce the discharge capacity of the project. For riprap areas above the 4 or 5 percent exceedence flow line, consideration may be given to overlaying the riprap with soil and sod to facilitate maintenance by mowing rather than by hand or defoliants. This may be particularly appropriate for riprap protecting against eddy action around structures such as gate wells and outlet works in levees that are otherwise maintained by mowing. Recognizing that vegetation is, in most instances, inimical to riprap installations, planned use of vegetation with riprap should serve some justifiable purpose, be accounted for in capacity computations, be controllable throughout the project life, have a strengthened riprap design that will withstand the additional exigencies, and account for increased difficulty of inspection.

Section VI
Quality Control

3-15. Quality Control

Provisions should be made in the specifications for sampling and testing in-place riprap as representative sections of revetment are completed. Additional sample testing of in-place and in-transit riprap material at the option of the Contracting Officer should be specified. The primary concern of riprap users is that the in-place riprap meets specifications. Loading, transporting, stockpiling, and placing can result in deterioration of the riprap. Coordination of inspection efforts by experienced staff is necessary. Reference EM 1110-2-2302 for detailed sampling guidance and required sample volumes for in-place riprap.